Verification of the Solar Dynamics Observatory High Gain Antenna Pointing Algorithm Using Flight Data

Kristin L. Bourkland* and Kuo-Chia (Alice) Liu†
NASA Goddard Space Flight Center, Greenbelt, MD, 20771, US

The Solar Dynamics Observatory (SDO), launched in 2010, is a NASA-designed spacecraft built to study the Sun. SDO has tight pointing requirements and instruments that are sensitive to spacecraft jitter. Two High Gain Antennas (HGAs) are used to continuously send science data to a dedicated ground station. Pre-flight analysis showed that jitter resulting from motion of the HGAs was a cause for concern. Three jitter mitigation techniques were developed and implemented to overcome effects of jitter from different sources. These mitigation techniques include: the random step delay, stagger stepping, and the No Step Request (NSR).

During the commissioning phase of the mission, a jitter test was performed onboard the spacecraft, in which various sources of jitter were examined to determine their level of effect on the instruments. During the HGA portion of the test, the jitter amplitudes from the single step of a gimbal were examined, as well as the amplitudes due to the execution of various gimbal rates. The jitter levels were compared with the gimbal jitter allocations for each instrument. The decision was made to consider implementing two of the jitter mitigating techniques on board the spacecraft: stagger stepping and the NSR.

Flight data with and without jitter mitigation enabled was examined, and it is shown in this paper that HGA tracking is not negatively impacted with the addition of the jitter mitigation techniques. Additionally, the individual gimbal steps were examined, and it was confirmed that the stagger stepping and NSRs worked as designed. An Image Quality Test was performed to determine the amount of cumulative jitter from the reaction wheels, HGAs, and instruments during various combinations of typical operations. The HGA-induced jitter on the instruments is well within the jitter requirement when the stagger step and NSR mitigation options are enabled.

Nomenclature

L_{NSR} = Limit to ignore No Step Requests
N_{cycle} = Number of GCE cycles since last gimbal step
Δt = Algorithm timestep
θ_{calc} = Desired gimbal angle relative to current position
θ_{cmd} = Commanded gimbal position
θ_{des} = Desired gimbal position
θ_{error} = Relative gimbal pointing error
θ_{meas} = Measured gimbal position
θ_{traj} = Gimbal trajectory position
ω_{max} = Maximum rate
ω_{traj} = Trajectory rate

I. Introduction

THE Solar Dynamics Observatory (SDO) is a NASA spacecraft, designed to observe the Sun and relay science data to a dedicated ground station at all times. SDO, shown in Figure 1, is in an inclined geosynchronous orbit and has five nominal modes of operation (Sun Acquisition, Inertial, Science, Delta-V, and Delta-H), plus a Safehold.[1] The spacecraft has three science instruments: the Atmospheric Imaging Assembly (AIA), the Helioseismic and Magnetic Imager (HMI), and the Extreme Ultraviolet Variability Experiment (EVE), all of which require a tight Sun-pointing inertial attitude. SDO's attitude sensors include a suite of sixteen coarse Sun sensors, two star trackers, an inertial reference unit, a digital Sun sensor, and four AIA guide telescopes, one of which is designated the controlling guide telescope. The attitude control actuators consist of four reaction wheels and a suite of eight thrusters. In addition, SDO has two High Gain Antennas (HGAs) which send science data to the ground.

*ACS Analyst, Attitude Control Systems Engineering Branch/Code 591
†ACS Analyst, Attitude Control Systems Engineering Branch/Code 591, AIAA Lifetime Member

SDO launched on February 11, 2010 at 15:23 UTC.[2] Deployment of the HGAs followed approximately 3 hours later, and the HGA gimbal initialization occurred on March 1, 2010. SDO reached its mission orbit on March 16, 2010, and gimbal checkout occurred on March 17, 2010. All instrument calibrations and operational checkouts were completed in order for official nominal science operations to begin on May 17, 2010.

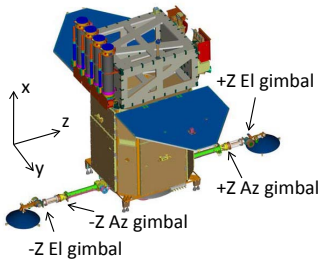


Figure 1. Solar Dynamics Observatory

II. High Gain Antenna Overview

The SDO spacecraft has two HGAs used to send science data to a dedicated ground station in White Sands (WS), New Mexico. In order to meet the science data capture budget, the HGAs must be capable of transmitting large quantities of data to the ground for a large percentage of the time. The HGAs consist of two dual-axis antennas driven by stepper motors, which can be commanded to a maximum rate of 1800 deg/hr (0.5 deg/sec). The azimuth gimbal on each antenna is capable of a full, 360° range of motion, with no unwinding necessary. The elevation gimbals are restricted to $\pm 69^\circ$.

A. HGA Target Generation

The two HGA antennas transmit data at all times, but only a single antenna is required to point to the ground station in order to meet the transmission rate requirement. The HGAs have varying blockage patterns over the course of each year with four distinct seasons. In the first season, the +Z antenna has an unobstructed view of the WS ground station while the -Z antenna is blocked. The third season is opposite, with the -Z antenna unobstructed and the +Z antenna blocked. During these times, the unobstructed antenna points to WS and the blocked antenna points out to space. During the second and fourth seasons, both antennas have non-simultaneous blockage periods each day, and must handover WS transmission responsibilities to the unblocked antenna. Each of these seasons with handovers lasts approximately 72 days, with the antennas handing off control and slewing to and from ground station tracking every twelve hours. The previously non-tracking antenna slews back to the ground station by following a ground commanded trajectory and arrives approximately 5 minutes before the formerly tracking antenna slews away to point out into space. The equations used to determine the target and pointing angles for each gimbal are described in detail in Ref. 3.

The maximum operational rate of the gimbal to keep the HGAs tracking the ground station was determined by examining orbit predictions. Since SDO is in a circular orbit inclined 28°, the position of the ground station relative to the spacecraft changes over time. Figure 2 shows the gimbal position required to point at the ground station, and Figure 3 shows a calculation of the gimbal rate required to maintain ground station tracking. The azimuth gimbals are required to move as fast as 33 deg/hr (approximately 0.01 deg/sec) in order to maintain track during certain portions of the year, well within the hardware's capability.

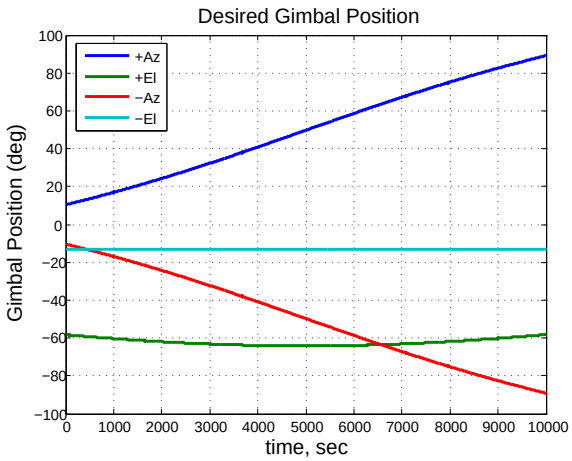


Figure 2. Desired Gimbal Position

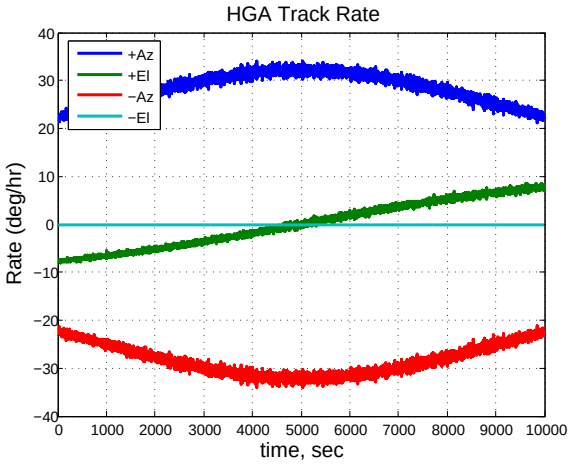


Figure 3. Required Gimbal Slew Rate

B. HGA Commanding

The Attitude Control System (ACS) flight software runs at 5 Hz, and the Gimbal Control Electronics (GCE) run at 200 Hz. Therefore, there are 40 opportunities for the GCE to pulse during each ACS cycle. However, there is a limitation of approximately 66.7 pulses per second (1800 deg/hr), or 1 pulse every 3 GCE cycles, placed on the GCE command by the gimbal electronics. If the gimbals are commanded at a higher rate, there is a possibility of GCE commands being dropped and an inaccurate response being received from the gimbals.

The command from the ACS controller to the GCE consists of 5 parts: The number of pulses to be applied, the direction of pulsing, the delay time in GCE cycles from the beginning of the ACS cycle, the interval time in GCE cycles between subsequent pulses, and the type of command (unchanged for ACS commanding). A further description of the commands to the GCE can be found in Ref. 3. A simplified version of the pulse command definition is pictured in Figure 4. Here, the ACS cycle is shown as 5 Hz, but the GCE cycle is reduced to 50 Hz for simplicity. The arrows represent the time of gimbal step, and the first step delay and interval time are labeled.

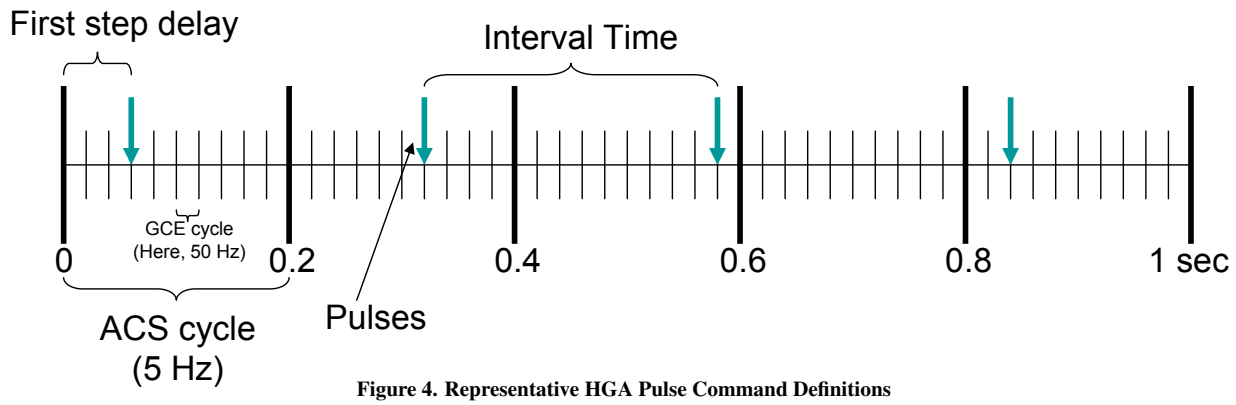


Figure 4. Representative HGA Pulse Command Definitions

Three types of targeting commands are sent from the ground to each antenna individually. The FULLPARK command slews to a set gimbal position and then parks both gimbals at that location. The HOLDTARGET command slews both gimbals to a calculated target and tracks the target upon arrival. The ELPARK command is a combination of the previous two commands. It parks the elevation gimbal at a set gimbal position and allows the azimuth antenna to track a given target. The ELPARK command is used to park the elevation of the non-tracking antenna while allowing the azimuth gimbal angle to match the azimuth of the tracking antenna. This motion ensures that the non-tracking antenna does not point at the Earth or irradiate the Clarke Belt.[4]

There are two different components of the tracking rate that are commanded from the ground. The *trajectory rate*, ω_{traj}, is the long term, or averaged, rate at which the gimbals need to move in order to reach, or maintain, their target. The *maximum rate*, ω_{max}, is the absolute maximum speed at which the gimbals are permitted to move at the ACS cycle level to ensure that the trajectory rate is met while allowing for scheduled periods of no antenna motion. Figure 5 is a visualization of these two terms. In this example, the maximum rate is the slope of the steep steps, or 3 rate units. The trajectory rate is the average rate over the entire plot, or 1 rate unit.

C. Basic HGA Control Algorithm

The ACS gimbal controller is a proportional controller which moves the HGA to the commanded target, whether it is a static gimbal angle or a moving ground target, as fast as the slew rates allow. After arrival, the controller holds the HGA on the given target, allowing for gimbal motion when the target moves. The commanded gimbal motion is constrained by the gimbal motor hardware, software command limitations, and slew restrictions from the attitude control system.

III. Jitter

The AIA and HMI instruments are sensitive to high frequency pointing perturbations and have sub-arcsec level line-of-sight (LOS) jitter requirements.[5] The RMS (Root Mean Square) LOS tilt and tip angles of the instruments are used as the measure of jitter throughout this analysis, with a requirement to keep the angles reported by the HMI instrument below 94 milli-arc-second (masec) 1σ, and the angles reported by the AIA instrument below 106 masec

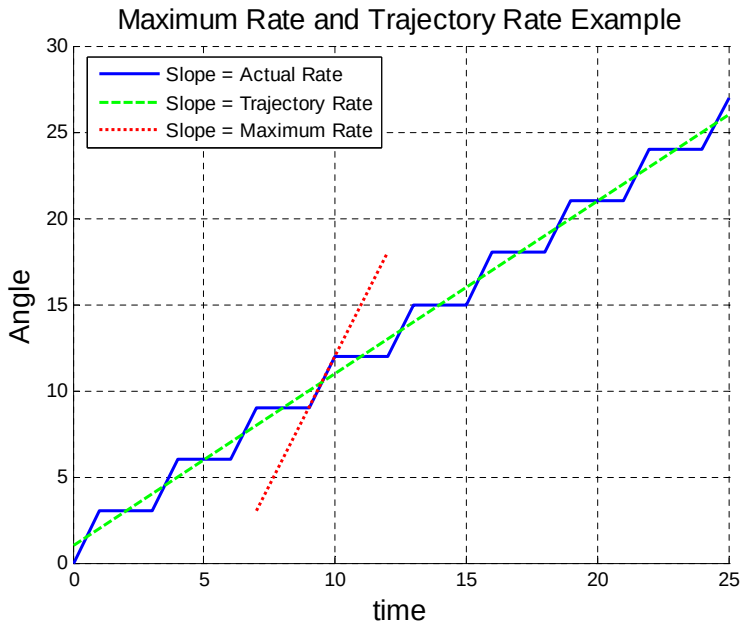


Figure 5. Maximum and Trajectory Rate Definitions

1σ. Pre-flight analysis and testing showed that the amount of jitter on the spacecraft due to motion of HGAs exceeded the jitter allotment.[6,7] Three methods of HGA jitter mitigation were included in the ACS HGA algorithm.[3]

A. Jitter Mitigation

One method of jitter mitigation included in the ACS HGA algorithm is the random first step delay. This mitigation method is necessary because the interaction of successive gimbal steps may lie on a jitter-critical structural mode. One of the commands sent to the GCE is the number of GCE cycles to wait before stepping the gimbal motor. In order to avoid the cadence of the gimbal steps hitting a jitter-critical mode, a small, pre-determined, pseudo-random number is added to the first step delay of each ACS cycle. This technique causes successive steps from the same actuator to be output at partially randomized times because the gimbal steps are no longer evenly spaced out.

A second method of jitter mitigation is stagger stepping. It is possible for the gimbal motions from different actuators to interact if one actuator takes a step during the ringdown period of a step from another actuator. This response may be constructive and cause the amount of jitter on the spacecraft to increase. To avoid this, stagger stepping can be implemented to forbid the positive and negative antennas from moving their gimbals during the same ACS timestep. This mitigation technique removes the possibility of constructively adding jitter from the two antennas.

A third method of jitter mitigation is the inclusion of an instrument No Step Request (NSR). A concern arose that a single gimbal motor step created jitter that is above the permitted levels for the instruments. Jitter is of the most concern to AIA and HMI when the instruments are taking images. The ACS HGA controller allows the instruments to request that the gimbals do not move during the cycles when they open their shutters. A check exists to ensure that the gimbals remain pointing to the target or will arrive at their target within an allotted time, within a tolerance, even if gimbal motions are delayed. If too many consecutive NSRs are sent by the instruments and the pointing becomes in danger of being compromised, the requests are rejected. As the pointing error of the gimbals increases, requests from the AIA instrument are rejected first, with HMI's NSRs rejected when the error is higher.

B. Jitter Mitigation Algorithm

When the jitter mitigating techniques are included, the algorithm for controlling the HGAs becomes more complicated. While the inclusion of the random first step delay and the stagger stepping techniques do not require a change to the format of the basic algorithm, the NSRs require knowledge of whether or not the HGAs are reaching the target in the allowed time and maintaining pointing within tolerance. If the instruments send too many NSRs and the HGA pointing falls behind, the controller needs the capability to know when to reject requests.

The first step in the jitter mitigating algorithm is calculating the desired gimbal target, θ_{des}. The HGA algorithm

deals with all gimbal angles in counts, which range from 0 to 48000, where 1 count is equal to 0.0075°. The following description makes the assumption that the algorithm is implemented in a way that the azimuth counter properly rolls over when reaching the end of the range. The targeting portion of the algorithm takes the position of the ground station (or other target) and converts it into a set of desired azimuth and elevation angles for each gimbal. Further information about the targeting algorithm is detailed in Ref. 3.

Once the desired target for each gimbal is known, the gimbal trajectory position to the target, θ_{traj}, is determined. As described previously, the rate trajectory, ω_{traj}, is a pre-determined value representing the rate at which the gimbals need to move in order to reach or maintain their target. The gimbal trajectory, therefore, is the number of gimbal steps for an ACS cycle that the gimbal motors must move to either slew to the target or maintain track. The number of steps is determined by taking the difference between the previous commanded gimbal position and the desired final gimbal position and saturating to the value of the maximum allowed change of each gimbal during the current ACS cycle, as shown in Eq. (1).

$$\theta_{traj} = \max\Big(-\omega_{traj} \cdot \Delta t, \min\big(\omega_{traj} \cdot \Delta t, \theta_{des} - \theta_{cmd}(k-1)\big)\Big) \tag{1}$$

Here, θ_{traj} is the gimbal trajectory position, ω_{traj} is the pre-determined trajectory rate limit, θ_{des} is the desired final gimbal position, $\theta_{cmd}(k-1)$ is the previous commanded gimbal position, and Δt is the algorithm timestep.

The commanded ω_{traj} following gimbal position for the current timestep is calculated in Eq. (2), which takes the previous commanded gimbal position and adds the change in angle based on the trajectory.

$$\theta_{cmd}(k) = \theta_{cmd}(k-1) + \theta_{traj} \tag{2}$$

The desired gimbal angle relative to current position (θ_{calc}) and the relative gimbal pointing error (θ_{error}) are computed in Eq. (3) and Eq. (4).

$$\theta_{calc} = \theta_{cmd}(k) - \theta_{meas} \tag{3}$$

$$\theta_{error} = \theta_{des} - \theta_{meas} \tag{4}$$

In flight software applications, the above equations are modified to take the difference between the two sets of gimbal counts, correct for rollover, and accept the difference with the smallest magnitude, either positive or negative.

Once the desired gimbal position relative to the current position is known, the command outputs for the pulse counts, interval time, first step delay, and direction are determined. The number of GCE cycles since the last gimbal motion (N_{cycle}) is also calculated and kept track of in order to honor the limit of the pre-determined maximum rate, ω_{max}. If the random step delay portion of the jitter mitigation is enabled, it is included here by adding a pseudo-random number to the first step delay and recalculating N_{cycle}.

After calculating a nominal command sequence, the No Step Request flag is checked and the calculated gimbal position is compared with the limit of allowed deviation from the trajectory, L_{NSR}. If NSRs are allowed, a NSR flag is high, and $\theta_{calc} < L_{NSR}$, then the gimbal command during that timestep is zeroed out and N_{cycle} is readjusted.

Stagger stepping only allows one antenna to move during a single timestep. If the stagger stepping flag is enabled, a check is performed to see which antenna moved most recently. If only one antenna is commanded to move, the algorithm proceeds with no change to the gimbal commands. However, if both antennas are commanded to move, the gimbal commands to the antenna that moved most recently are zeroed and N_{cycle} for those gimbals is adjusted accordingly.

C. Pre-Flight NSR Analysis

In order to stay pointed at the ground station, the gimbal trajectory rate must be set to be larger than the fastest rate that the gimbals are required to move in order to maintain track. The maximum gimbal rate required for SDO to track WS is 33 deg/hr, as shown in Figure 3. The smallest allowable maximum rate to avoid rejected NSRs and remain tracking the ground station can be calculated.

For margin, it is assumed that a trajectory rate, ω_{traj}, of 35 deg/hr is required. The projected HMI NSR cadence allows motor stepping for one second, then requests no steps for one second. Because of this, the gimbals are required to move twice the distance for half of the time and then be motionless for the other half of the time. The calculated rate then becomes:

$$\omega_{traj} = 2 \times 35 \frac{\text{deg}}{\text{hr}} = 70 \frac{\text{deg}}{\text{hr}} = 2.5926 \frac{\text{cnt}}{\text{sec}} \tag{5}$$

This result rounds up to a requirement of 3 gimbal steps per second in order to ensure that ω_{traj} is greater than 35 deg/hr.

Based on the assumed HMI cadence, there are 5 ACS cycles available for the gimbals to move for the one second they are permitted to step between NSRs. Because of the limitations of stagger stepping, there are an odd number of cycles (5) in which the HGA system needs to move an even number of antennas (2). Therefore, the gimbal motion must be completed in 2 ACS cycles per antenna, with one ACS cycle nominally having no commanding. The only way to accomplish 3 gimbal steps within 2 cycles is to move twice within one ACS cycle, with the antenna motion taking the form of Figure 6.

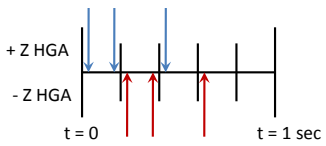


Figure 6. Antenna Motion

The maximum rate, ω_{max}, is calculated with an interval time of 39 GCE cycles (which spreads the two gimbal pulses occurring in the same cycle as far apart as possible), and is equal to 138.46 deg/hr. This value is rounded up to 140 deg/hr.

Figure 7 shows an expected gimbal step distribution during nominal ground station tracking while HMI is sending NSRs. The red line shows the time of no step request, and the colored boxes represent the time of gimbal motion for a given antenna. The -Z antenna is in ELPARK mode, where the elevation gimbal is held at a fixed position, and the +Z antenna is in HOLDTARGET mode at a point in the orbit where the required azimuth motion is much greater than the required elevation motion.

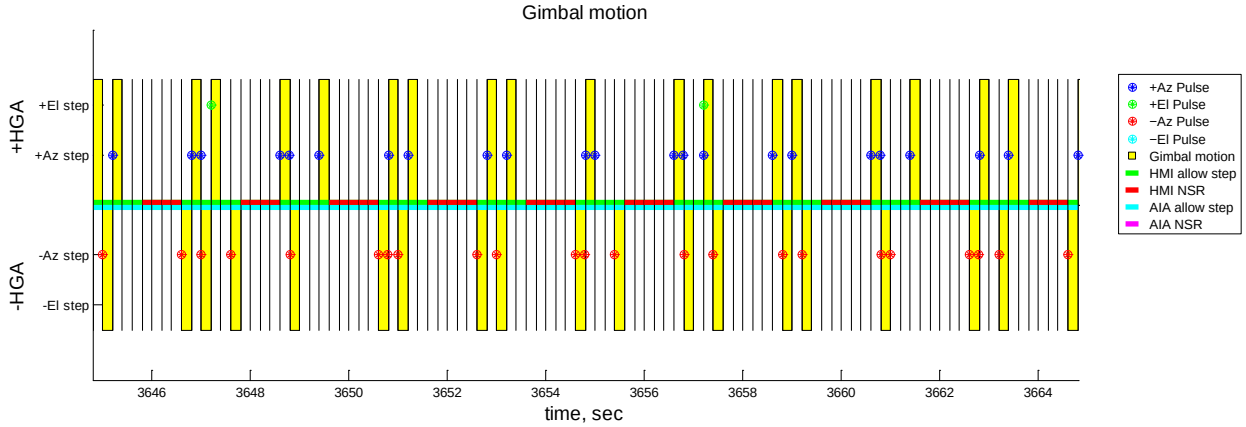


Figure 7. HMI No Step Requests

The HMI NSR cadence used in this analysis is actual data obtained from the HMI instrument. The pattern doesn't exactly follow the one second on, one second off predicted cadence. At times, the NSR can last for up to 1.2 seconds with only 0.8 seconds where stepping is allowed. This cadence should not cause a problem with the previously calculated trajectory rate because the nominal case only used four of the five available ACS cycles for stepping. The overall HMI-allowed duty cycle was 42.7%.

It is important for HMI to have no HGA motion during their camera imaging, and the AIA instrument desired to have the NSR capability, too. As mentioned previously, the AIA NSR was considered secondary to HMI, so theirs was rejected when the pointing error was lower than when the HMI request was rejected. The expected cadence of the AIA instrument NSR is on for one second every 10 seconds.

Figure 8 shows the expected gimbal step distribution while both HMI and AIA are sending NSRs. Here, the purple line shows the time of AIA NSR.

The cadence of the NSRs obtained from AIA had a duty cycle of 12%. The AIA and HMI instruments do not coordinate their picture taking times, so it is possible, as shown here, for an overlap in NSRs to occur. In this instance, three continuous seconds of NSRs were commanded, which caused the pointing of the gimbal to fall behind. Since AIA has a lower limit for rejecting NSRs, some of the AIA NSRs were rejected during this time, as shown in the figure.

Statistics on the NSRs from the two above cases are summarized in Table 1. During the simulations, no NSRs were rejected for either case. During the case where AIA NSRs were sent, 1.6% of the AIA NSRs were rejected. The earlier prediction of trajectory rate expected 3 gimbal steps per second when only HMI NSRs are sent, and this result occurred in the simulation. That value increases to 4 when AIA NSRs are also sent.

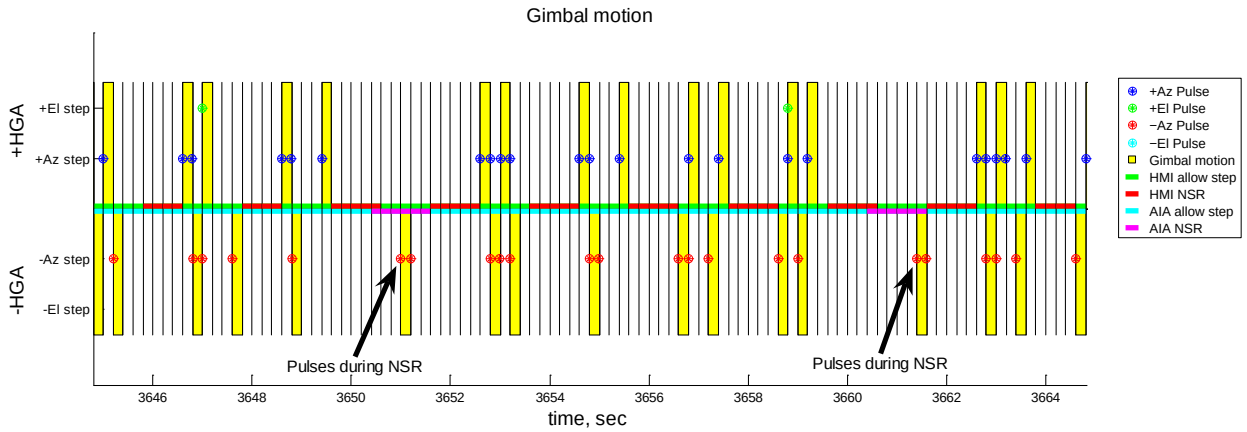


Figure 8. HMI and AIA No Step Requests

Table 1. Summary of Commands

NSR Allowed	HMI only	HMI and AIA
HMI NSRs	21364	21364
HMI NSRs Rejected	0	0
AIA NSRs	0	5967
AIA NSRs Rejected	0	95
Maximum HGA pulses per gimbal per ACS cycle	2	2
Maximum HGA pulses per gimbal cycle per sec	3	5
Maximum pointing error (counts)	3	4

IV. Flight Results: Jitter Test

A jitter test was performed from March 31 to April 2, 2010 to take a closer look at the sources of jitter on the spacecraft.[5] The jitter test as a whole looked at the amount of jitter caused by motion of the reaction wheels, the HGAs, and the AIA and HMI instruments.

The HGA portion of the test consisted of two sections: the single step test and the rate test. During the single step test, the HGA gimbals started at selected angles and moved two steps on the azimuth gimbal and two steps on the elevation gimbal, with a 10 second wait in between each step. During the rate test, the gimbals were commanded to the next target at rates that increased every 10 seconds, finishing with a command to complete the move to the next target at maximum speed. The commanded rates varied from 13.5 deg/hr to 135 deg/hr, with the move to the next target taking place at the maximum speed of 1800 deg/hr. A plot of the commanded jitter test gimbal angles is shown in Figure 9. The desired and measured gimbal angles during one leg of the test are shown in Figure 10. Here, it is shown that the gimbal rate begins low at the beginning of the leg and slowly increases until the maximum rate is commanded.

A. Jitter from HGA Motion

The jitter test produced results that showed how much jitter was created both from a single step of a gimbal and while the gimbals were moving at different step rates. The worst case results for the jitter on the AIA instrument are shown in Figure 11, where the positive azimuth angle is located at -90° and the positive elevation gimbal moves from 45° to -45°, and the negative gimbals remain fixed. Here, it is shown that the motion of the azimuth gimbal motors are barely detectable by AIA, but each of the individual elevation steps are above the 106 masec 1σ jitter allocation. Increasing the step rate of the gimbals does not have an increased effect on jitter until 140 seconds into the test, which corresponds to a commanded gimbal rate of the maximum 1800 deg/hr and is outside the nominal commanded gimbal rate.

The worst case jitter results for the HMI instrument resulted when the negative azimuth gimbal was located at 180°, the negative elevation gimbal angle moved from -45° to 0°, and the positive gimbals remained fixed, which is shown in Figure 12. In this case, the jitter resulting from azimuth gimbal motions is small relative to the jitter resulting from the elevation gimbal motions. The jitter due to a single step of the elevation gimbals is close to the jitter

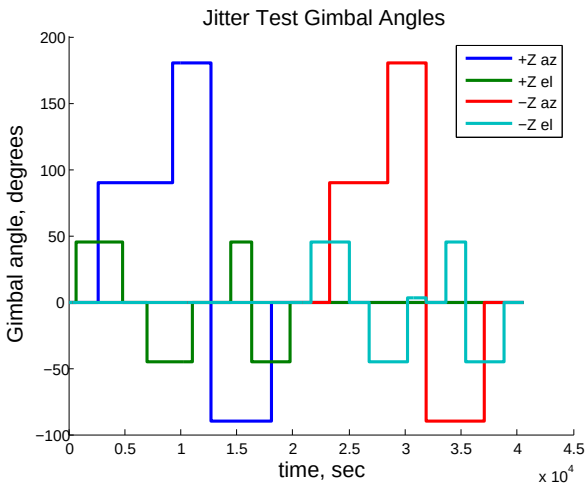


Figure 9. Jitter Test Angles

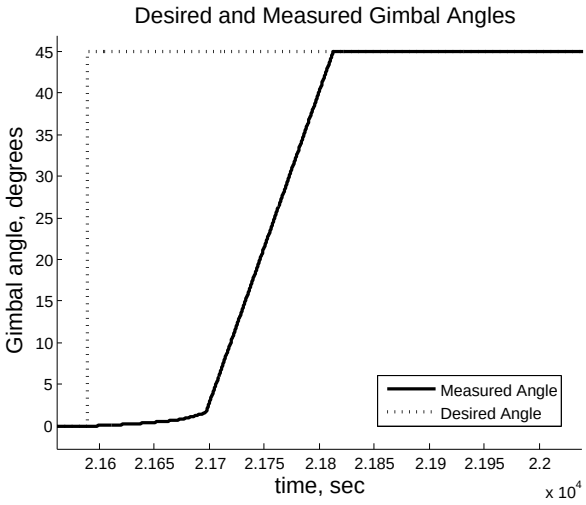


Figure 10. Increase Rates

allocation of 94 masec 1σ. Increasing the step rate of the gimbals begins to have an undesired effect on jitter when time is 135 seconds, which corresponds to a gimbal rate of the maximum 1800 deg/hr.

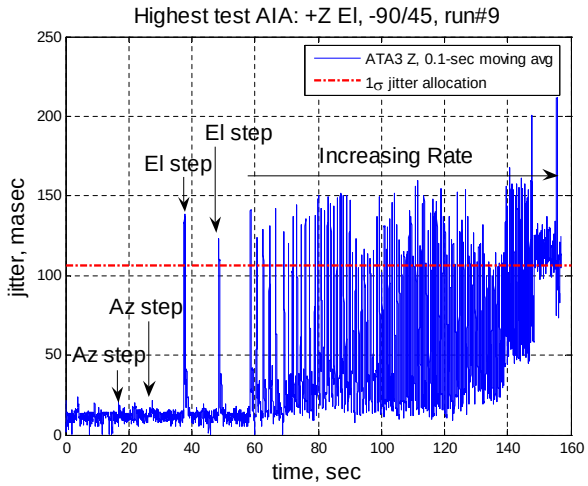


Figure 11. AIA Jitter

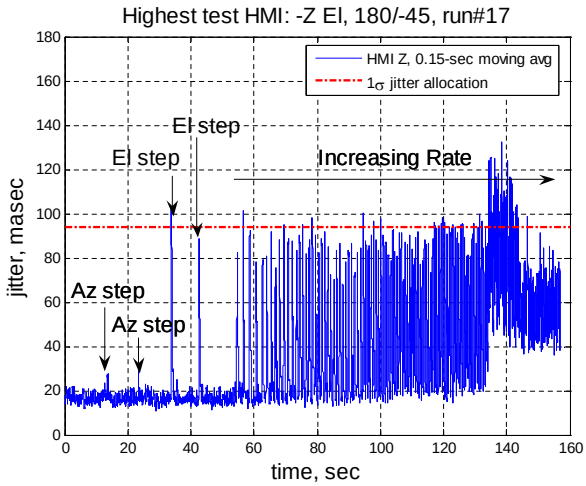


Figure 12. HMI Jitter

B. Readback Delay

Readback delay of GCE data causes the telemetered position of the gimbals to be incorrect at times. If a gimbal step is scheduled to occur in the later portion of an ACS cycle, it will not be read during that cycle, leaving the current position lagging behind. The unread gimbal steps will appear in the following ACS cycle.

The individual steps of each gimbal were examined during the various rates of the HGA slew. Figure 13 shows the individual gimbal steps for one gimbal when commanded to move at a rate of 28.871 deg/hr, and Figure 14 shows the steps when the gimbals are commanded to a trajectory rate 1350 deg/hr with a maximum rate of 1800 deg/hr.

Here, each individual ACS cycle is shown in a separate row, with each GCE cycle shown as a separate column. The black circles represent an opportunity for the gimbal to step (40 opportunities per ACS cycle). A blue mark in a circle represents a time when a gimbal moves and the telemetry reports the step. A red mark in a circle represents a gimbal motion that is not detected during that ACS cycle. A green mark at the end of the row represents a GCE pulse that is reported by telemetry, but didn't actually occur during that ACS cycle. The total number of red and green marks are equal, since a missed pulse is falsely reported during the next cycle.

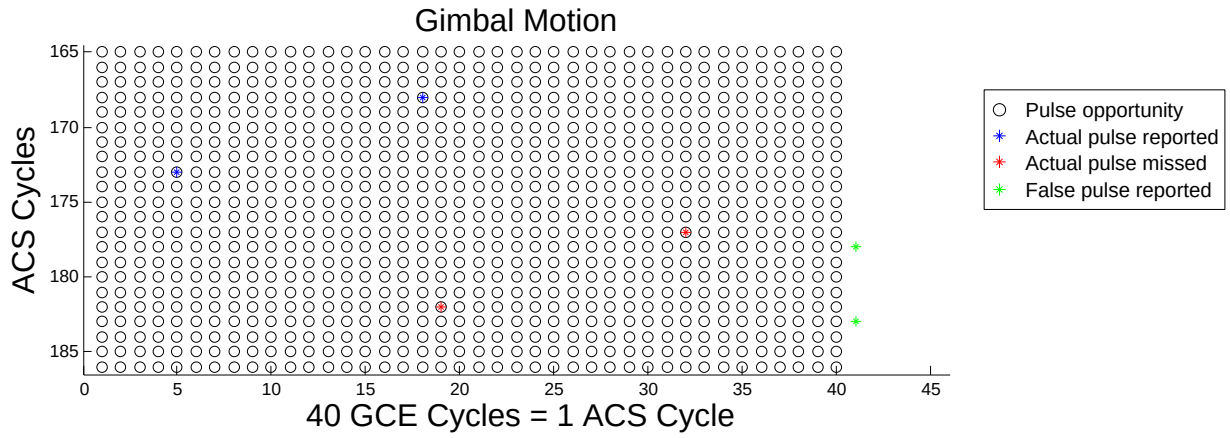


Figure 13. Readback at 28.871 deg/hr

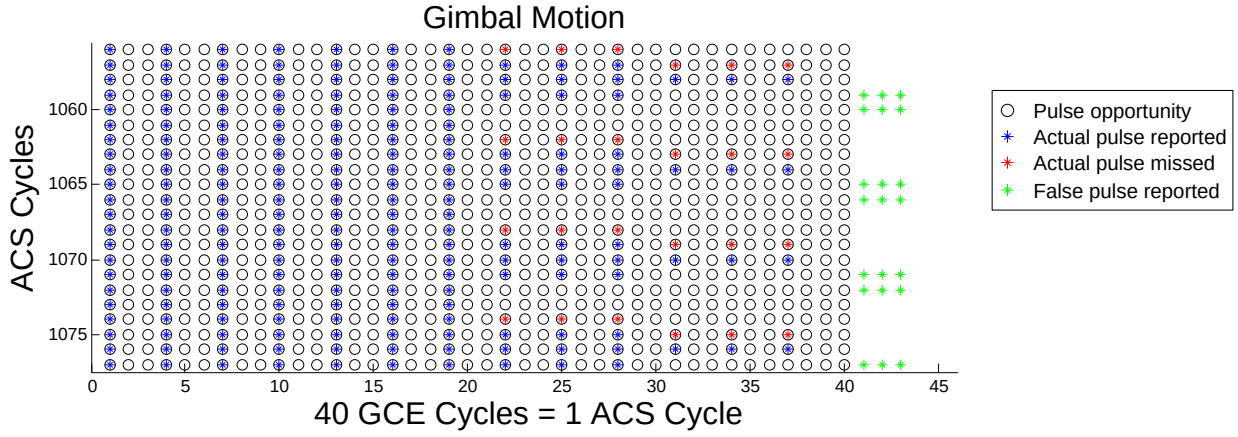


Figure 14. Readback at 1800 deg/hr

In Figure 13, the GCE steps occur every 187 GCE cycles. It is clear to see that the steps which occur during GCE cycles 1 through 18 are reported correctly, while steps occurring during GCE cycles 19 through 40 experience a readback delay and are not reported until the following timestep. This time delay matches predictive calculations made by the flight software team.

In Figure 14, the maximum rate constrains the steps to be no more often than every three GCE cycles. The trajectory rate of 1350 deg/hr nominally would command 10 pulses during each ACS cycle. However, since the last three pulses occur after the 18th GCE cycle, the readback delay causes a slightly different result. When three pulses are lost in telemetry due to readback delay, the controller attempts to compensate and reissue the step commands during the next ACS cycle. After a few cycles, the controller has overcommanded the steps, and the telemetry detects a gimbal position that is greater than desired. The controller then backs off, and commands less than the nominal 10 pulses. These actions cause the true rate of slew of the gimbal to oscillate.

C. True Versus Measured Gimbal Position

As mentioned previously, because of readback delay, the true gimbal position is not always correctly reported. A plot of the difference between the true and measured gimbal position for a gimbal during one leg of the jitter test is presented in Figure 15. The gimbal rate of motion is represented by the thick black line.

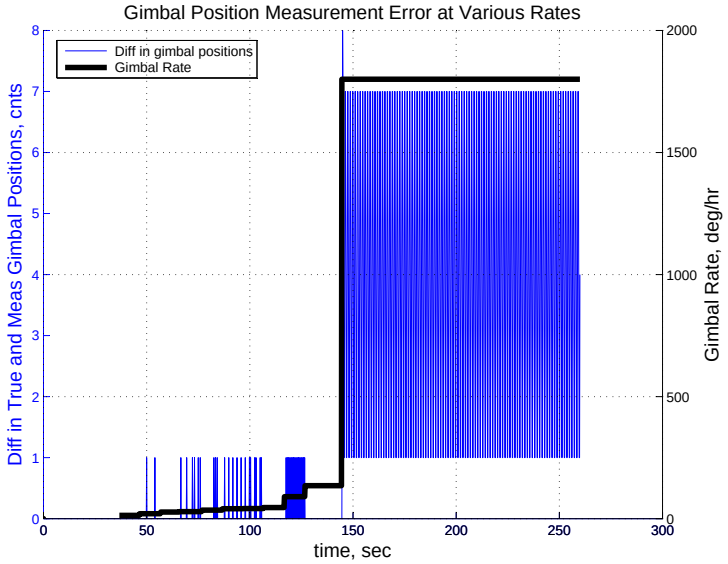


Figure 15. Error at Rates

During the rate ramp up test, the difference between the true and measured gimbal position remained at zero or one count. When the gimbals were commanded to a max rate of 1800 deg/hour, the error increased to one to seven counts. However, since the gimbal rate will never be set to the maximum rate of 1800 deg/hr during nominal mission operations, the difference in the true and measured gimbal positions will not cause problems with gimbal pointing.

V. Flight Results: Handovers

Jitter mitigation techniques were tested during nominally planned HGA handovers in the checkout stage of the mission. The results from a handover with all jitter mitigation techniques turned off were compared with a handover utilizing the mitigation techniques.

A. No Jitter Mitigation

The measured, desired, and predicted gimbal angles during a handover with no jitter mitigation are plotted together in Figure 16. The start of each of the four legs of the handover are labeled in the plot, where leg one moves the +Z antenna from an ELPARK position pointing away from the Earth to the North Pole, leg two moves the +Z antenna from the North Pole to tracking at WS, leg three moves the -Z antenna from WS to the South Pole, and leg four moves the

-Z antenna from the South Pole to its ELPARK position pointing away from the Earth. The measured gimbal angles arrive at their target much faster than predicted in legs two and four, and slightly faster than predicted in legs one and three. This result was expected by the slew planners, who included conservatism in their estimates. The amount of pointing error during the slews is shown in Figure 17.

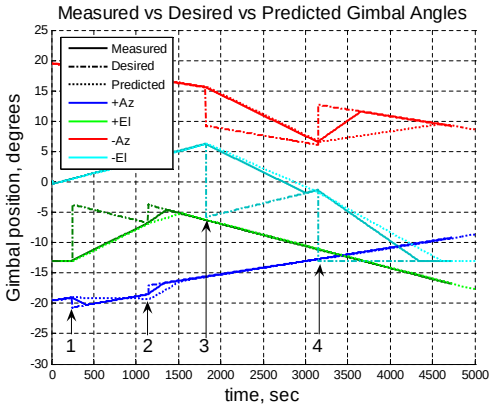


Figure 16. Measured vs Desired vs Predicted during Handover with No Jitter Mitigation

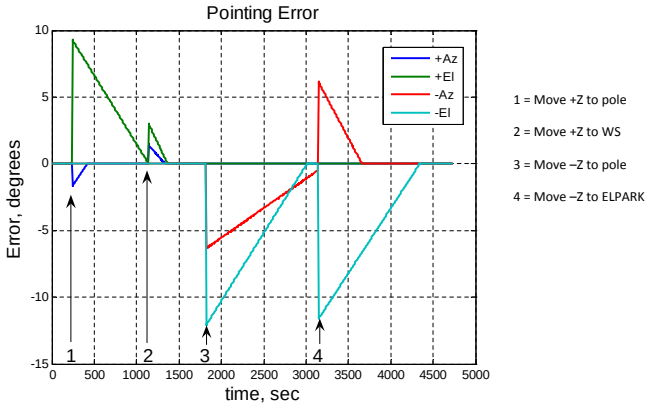


Figure 17. Pointing Error during Handover with no Jitter Mitigation

A plot of the actual gimbal rates during the handover is shown in Figure 18. During the handover slews, the trajectory rate is commanded 25 deg/hr on some legs and 35 deg/hr on other legs, with a maximum rate allowed to be 140 deg/hr. The actual instantaneous rate is measured to be as high as 68 deg/hr, although the high rate occurs as spikes instead of a sustained rate. A comparison of the desired and measured gimbal angles around the time of a maximum rate spike is shown in Figure 19. From this plot, it is possible to determine that the high instantaneous rate is due to noise causing the gimbal to move in the other direction for one cycle.

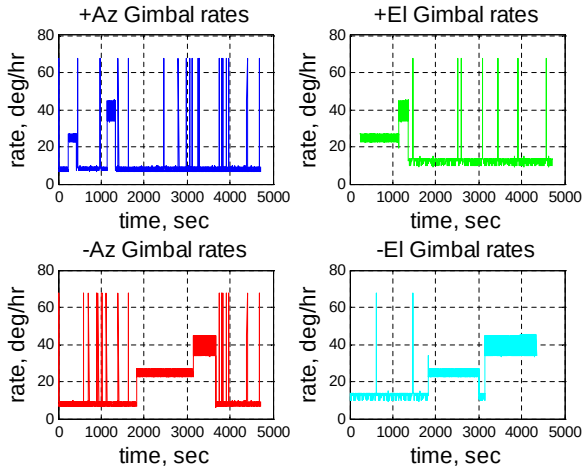


Figure 18. Gimbal Rates during handover with no mitigation

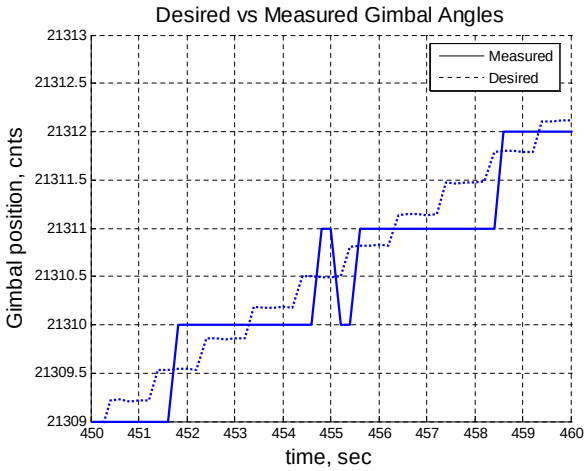


Figure 19. Change Direction During Handover

Figure 20 shows the time of gimbal motion during a portion of the nominal handover with no jitter mitigation. This plot shows that there are no NSRs sent by the instrument, so there is no limitation to the times when the gimbal can step. Additionally, stagger stepping is off, so the +HGA gimbals and -HGA gimbals are permitted to step at the same time, and can be seen stepping together in this data.

B. Stagger Stepping Plus NSR

A set of HGA data was collected during an HGA handover with the Stagger Stepping and NSR jitter mitigation techniques enabled. A plot of the measured versus desired versus predicted gimbal angles during the handover is

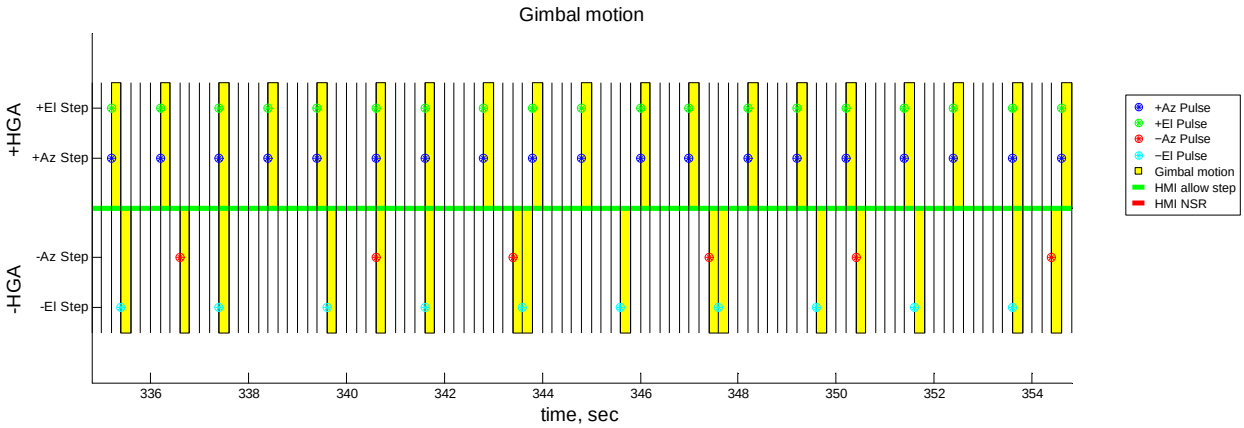


Figure 20. Handover with No Jitter Mitigation

shown in Figure 21. The times that the stagger stepping and NSR were enabled are shown in Figure 22. Both jitter mitigation techniques were enabled before the handover began.

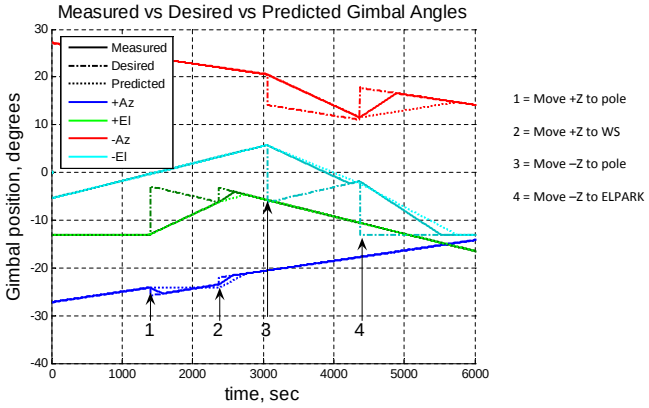


Figure 21. Measured vs Desired vs Predicted during Handover with Jitter Mitigation

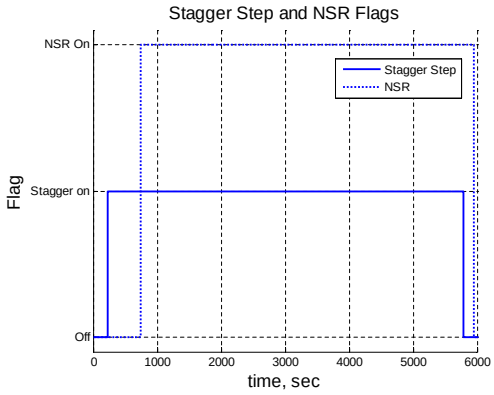


Figure 22. Time of Jitter Mitigation Enabling

A plot of the commanded HMI NSR cadence is shown in Figure 23. Stepping of the gimbals was allowed for 0.8 to 1 seconds, followed by no step requests lasting from 1 to 1.2 seconds. The duty cycle of the commanded NSR was 56.1%, which was slightly higher than the predicted duty cycle of 42.7%.

The gimbal error between the measured gimbal position and the desired gimbal position is shown in Figure 24, with dotted lines showing the limit of 7 counts for rejecting HMI NSRs. If an antenna is slowed down too much by the jitter mitigating techniques and begins to deviate from the planned trajectory, the commanded NSRs are ignored. During this set of handovers, the gimbal error between the measured and desired gimbal positions does not become larger than 3 counts, which is well under the limit of 7 counts, and no NSRs are ignored.

The rates during the handover of each gimbal is shown in Figure 25. During the gimbal slews, the trajectory rate is commanded to either 25 deg/hr or 35 deg/hr, and the maximum rate is commanded to 140 deg/hr. The instantaneous rate is measured to be as high as 140 deg/hr.

Figure 26 shows the time of gimbal motion during a portion of the handover with stagger stepping and NSRs enabled. The green line in the center shows the time that the gimbals are allowed to move when no NSRs are sent. From this plot, it is possible to see that there are no rejected NSRs because all gimbal steps occur in the green region. Additionally, stagger stepping forbids two antennas from moving during the same timestep. This plot shows that the stagger stepping technique is honored because there are no times when two antennas move together.

VI. Flight Results: Image Quality Test

The jitter tests described in Section IV. looked at the amount of jitter caused by individual motions of various mechanisms on the spacecraft. However, during the nominal mission, the different mechanisms have motions that act

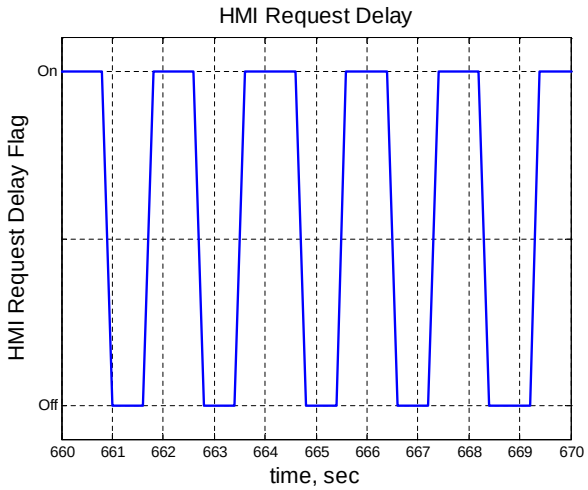


Figure 23. HMI Cadence

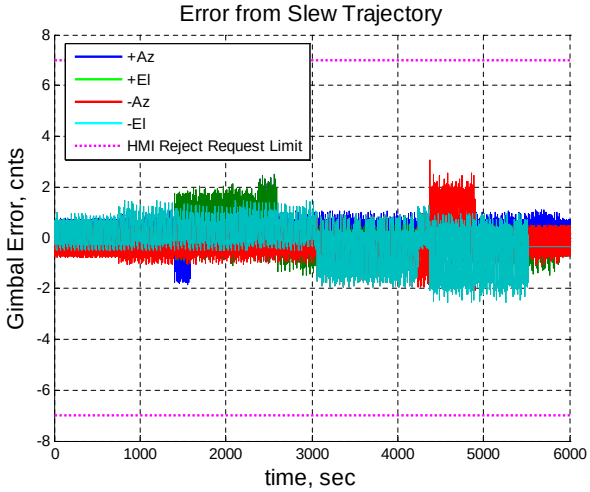


Figure 24. Rejected Request Limit

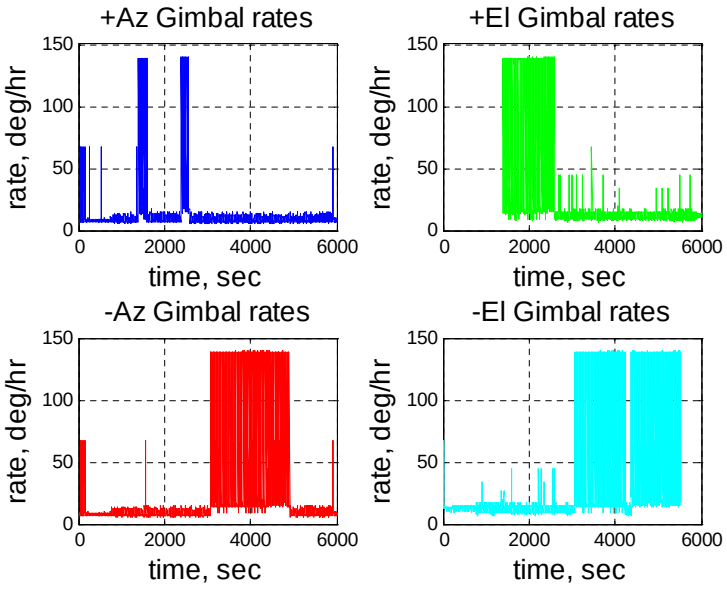


Figure 25. Gimbal Rates during Handover with Jitter Mitigation

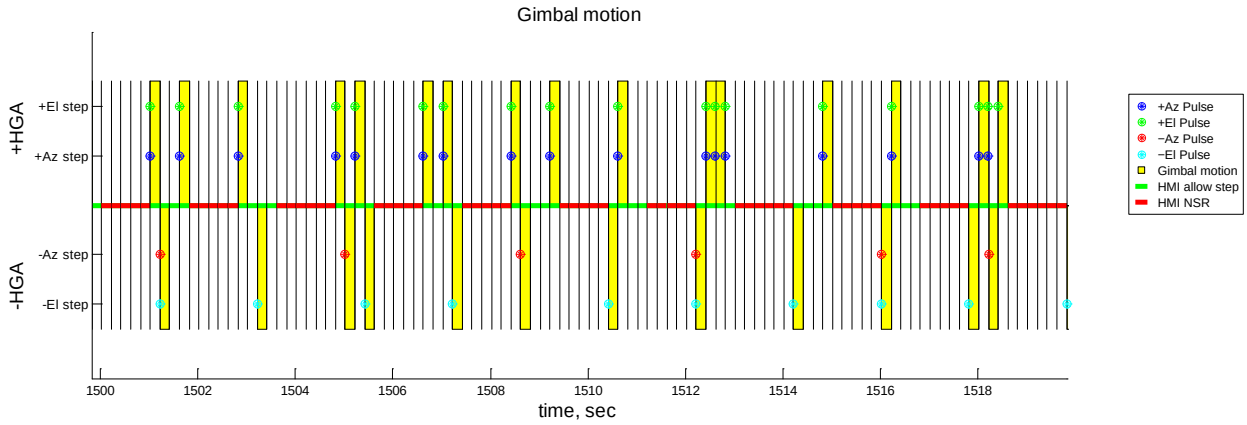


Figure 26. Handover with Jitter Mitigation

independently of each other, and therefore may have impacts on each other that is not seen in the individual jitter tests. Adding the worst-case estimates of each of the jitter sources is a way to find an upper bound on the jitter effects, but does not give a realistic picture of what the spacecraft will actually experience. The Image Quality Test was made up of 31 individual tests which looked at the amount of jitter measured by an instrument, in the form of RMS LOS tip and tilt angles, when combinations of mechanisms moved on the spacecraft. The test cases for the Image Quality test were chosen to sample a wide range of possible nominal cases, while worst-casing one mechanism at a time.

The moving mechanisms examined in this test included the HGA, the RWAs, and the three instruments: HMI, AIA, and EVE. The HGAs were set up to vary the motion of the gimbals, as well as vary whether or not stagger stepping and NSRs were enabled. The RWAs were changed in different tests to include low speeds, high speeds, zero crossings, or wheel speed sweeps. The HMI instrument was varied between no motion, a simple shutter snap, or its standard synoptic sequence. Similarly, the AIA instrument was varied between no motion, a simple shutter snap, and its standard synoptic sequence. The EVE instrument included either no motion, varying rates, or its calibration sequence.

Figure 27 shows the results for a portion of one case from the image quality test. Here, the HGAs were set to perform their daily handover, NSR commanding was enabled, and stagger stepping was enabled. The RWAs were set to low wheel speeds of less than 300 rpm. The HMI instrument was following its standard synoptic sequence and sending a nominal NSR sequence. The AIA instrument was also sending its standard synoptic sequence, and the EVE instrument was sending its non-calibration sequence.

The blue solid line shows the RMS HMI LOS tip and tilt angles in arcsecs. The red dotted line shows the HMI jitter requirement. The magenta box shows the times that the NSR flag is raised and gimbal stepping is not allowed. The black circles and vertical lines show the times of gimbal motion. The cyan box shows the actual time that an image is taken by the instrument.

From this figure, it can be seen that no gimbal steps are taken when the NSR flag is raised. Also, the jitter effect of the gimbal steps is noticeable in the HMI jitter data when the jitter level raises as the gimbals move. Most importantly, it is shown that the jitter level is well below the required jitter limit at the time that the image is taken by the instrument.

Ideally, both AIA and HMI NSRs should be used to reduce jitter. However, as shown in Section III..C., if both instrument NSRs are activated, it is possible to reject the AIA NSRs. Consequently, a more careful tracking of when AIA NSRs are rejected may be required by the Flight Operations and AIA teams. Fortunately, after examining the AIA images during the Image Quality Jitter Test, the AIA team decided that it was not necessary to invoke the NSR flag in order to obtain desirable science images. After the commissioning phase, SDO has been operating with only the HMI NSR activated to achieve its science requirements

VII. Conclusion

A new HGA jitter mitigating algorithm, with three methods of jitter mitigation, was designed for SDO and implemented in the on-board flight software. Flight data shows that the algorithm works as designed, with no degradation to HGA pointing performance, and reduces the jitter level of the antenna gimbal steps to level that is acceptable to the science instruments. A decision was made to enable the stagger stepping and HMI NSR mitigation techniques on

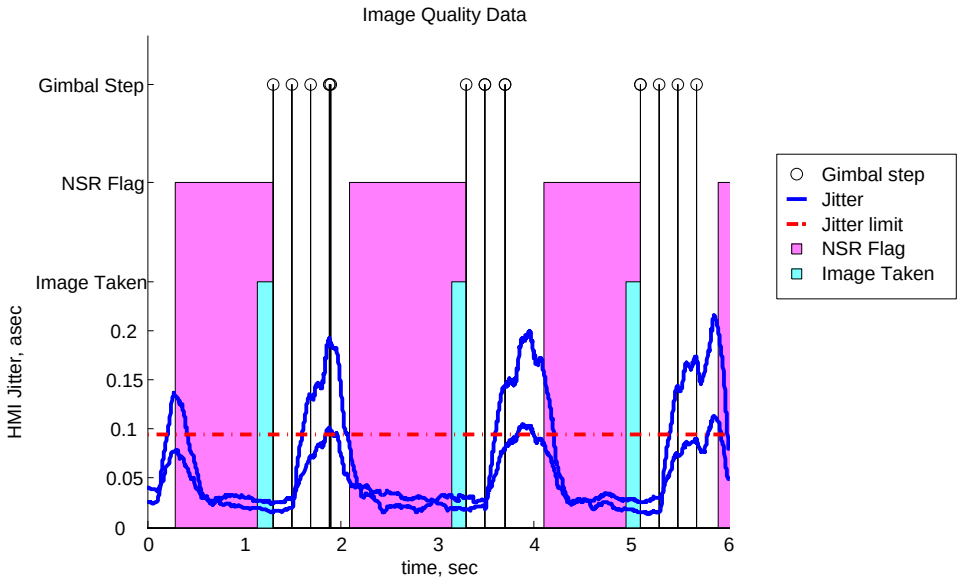


Figure 27. Image Quality Test Results

orbit for the duration of the mission. These two techniques reduce jitter sufficiently so that there is no need to enable the random step delay.

Acknowledgments

The authors would like to thank Seth Shulman and Wendy Morgenstern for their support in the development and execution of the HGA jitter tests, Carl Blaurock for his jitter analysis and jitter test planning support, and Peter Kutt for his numerous suggestions on the implementation of the HGA jitter mitigation in the flight software.

References

[1]Morgenstern, W. et al., "Solar Dynamics Observatory Guidance, Navigation, and Control System Overview," *AIAA Guidance, Navigation, and Control Conference*, August 2011 (to be published).

[2]O'Donnell, J. R. et al., "Solar Dynamics Observatory Launch and Commissioning," *34th Annual AAS Guidance and Control Conference*, February 2011.

[3]Bourkland, K. L., Liu, K.-C. A., and Blaurock, C., "A Jitter-Mitigating High Gain Antenna Pointing Algorithm for the Solar Dynamics Observatory," *International Symposium on Space Flight Dynamics*, 2007.

[4]Hashmall, J. A. and Mann, L., "Solar Dynamics Observatory High Gain Antenna Handover Planning," *International Symposium on Space Flight Dynamics*, 2007.

[5]Liu, K.-C. A., Blaurock, C. A., Bourkland, K. L., Morgenstern, W. M., and Maghami, P. G., "Solar Dynamics Observatory On-orbit Jitter Testing, Analysis, and Mitigation Plans," *AIAA Guidance, Navigation, and Control Conference*, August 2011 (to be published).

[6]Liu, K.-C. A. et al., "Jitter Test Program and On-Orbit Mitigation Strategies for Solar Dynamics Observatory," *International Symposium on Space Flight Dynamics*, 2007.

[7]Blaurock, C., Liu, K.-C., and Mule, P., "Solar Dynamics Observatory (SDO) HGAS Induced Jitter," *49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, April 2008.